THE INFLUENCE OF HARVEST SYSTEMS ON SEDIMENT DELIVERY ON THE MOUTERE GRAVELS

A dissertation submitted in partial fulfilment of the requirements for the degree of Bachelor of Forestry Science with Honours

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EXECUTIVE SUMMARY

Fine sediment suspended in waterways is one of the most significant pollutants associated with New Zealand plantation forests, adversely impacting the quality of downstream aquatic ecosystems, and tarnishing public perception of the forestry industry. Nelson Management Limited identified in their plan to improve sedimentation performance that a quantification of the ground disturbance for common harvest systems would help identify the sediment delivery risks for each system on the Moutere gravels. With a combination of ground survey and aerial photography techniques, soil disturbance patterns and sediment breakthroughs were observed over 16 harvested settings that had been exposed to at least one significant rainfall event. Of these sites, 11 sites were cable yarded, and five were ground-based.

For cable yarding sites, breakthroughs were observed every 190 m of ephemeral stream or every 4.55 ha of harvest area. For ground-based sites, on average a breakthrough was found for every 107 m of ephemeral stream or for every 1.82 ha over harvest area. All breakthroughs observed were into ephemeral streams. The majority of sediment breakthroughs were associated with earthworks or harvesting related soil disturbance, rather than landslides. For cable yarding systems, there were large areas of scalping observed, but this had little bearing on sediment delivery as 16 of the 26 breakthroughs were due to machine tracking on the slopes. For ground-based sites, 15 of the 25 breakthroughs were primarily caused by skid and spur roads. Roading density was the only significant predictor of sediment breakthroughs at the significance level $\alpha \leq 0.05$. On the Moutere gravels; slope, stream length per ha, crew and extraction method were not found to be significant predictors of sediment breakthroughs per ha. However, due to the limited selection of harvest settings, there was limited replication of the crew and extraction method factors, making any statistical differences difficult to detect.

The image classification method developed to estimate the bare soil percentage for a site was found to be insufficiently reliable to allow conclusions to be made from the data that was collected for each setting.

Managers should focus on reducing roading density through careful road placement and focusing on breaking the connectivity between sediment generated from earthworks and streams. Further study that focuses on quantifying the rate that sediment is delivered to ephemeral streams gets transported to perennial streams would show how significant the breakthroughs to ephemeral streams are to total sediment yields from harvested catchments.

Keywords: Sediment delivery; Harvest systems; Soil erosion; Moutere gravels

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1 INTRODUCTION

Elevated sediment yield from recently harvested stands is one of New Zealand plantation forestry's most prominent environmental concerns. Suspended sediment in waterways negatively impacts fish spawning and feeding behaviour. It also harms public opinion of the forestry industry. NIWA research conducted for the local councils has attributed much of the sediment in Tasman Bay to a plantation forestry source (Gibbs & Woodward, 2018), and several significant rainfall events in recent times are contributing to growing pressure on plantation forestry's license to operate in the region.

Nelson Management Ltd. (NML), the managers of Nelson Forests, have adopted a company culture of continuous improvement. As a part of this philosophy, they strive to continually improve their environmental performance. Specifically, in the context of this study they want to evaluate the practices they undertake to avoid, mitigate or remedy sediment delivery to waterways.

One element identified in their plan to improve sedimentation performance was to quantify the actual and relative ground disturbance for a range of common harvest systems within a common terrain and soil type, to identify the sediment connection risks for each system. In this study, through a combination of ground survey and aerial photography, recently harvested settings were assessed for sources of sediment generation and whether these delivered concentrated sediment to waterways. The ground disturbance associated with roads, skids, machine tracks, scalped ridges, and cutover was documented. This study would allow managers to get a clearer picture of where to focus their attention when trying to break the hydrological connectivity between sediment sources and streams for each system.

This report intends to identify the critical aspects of each harvest system that may require more attention to avoid, mitigate or remedy sediment connectivity. The harvest systems investigated were categorised by extraction system, including ground-based crews and cable yarding crews; integral tower yarders; and swing yarders. All surveys were done on a common terrain and soil type, the Moutere gravels, in the Tasman District of New Zealand.

2 LITERATURE REVIEW

This brief review of the literature is structured into three sections. The first section describes the significance of the problem of sediment in waterways, the second section reviews the mechanisms behind sediment generation and delivery in plantation forests; and the third describes the specific attributes of the soils in the study area.

2.1 THE SIGNIFICANCE OF SEDIMENT IN WATERWAYS

While sedimentation is a natural process, the frequency and intensity of ecologically significant events can be influenced by land use such as forest harvesting and the associated earthworks, and the level of disturbance they generate (Allen, 2004; Baillie & Neary, 2015). Forest catchments have been shown to exhibit highly elevated short-term sediment yields post-harvest (Fahey, Marden, & Phillips, 2003; Phillips, Marden, & Basher, 2012), with yields typically returning to pre-harvest levels within two to six years (Amishev, et al., 2014; Basher et al. 2011; Fahey and Marden 2006; Phillips et al. 2005).

Suspended fine (<2mm) sediment is one of the most significant pollutants associated with New Zealand plantation forests, adversely affecting downstream aquatic ecosystems. These impacts include decreases in macroinvertebrate abundance, richness, fish cover and spawning areas; decreases in stream clarity which in turn decrease fish feeding visibility resulting in higher mortality rates (Clapcott et al., 2011). In response to the negative environmental impacts, there are social consequences for plantation forestry's license to operate in the region. A study commissioned by the Tasman District Council and conducted by NIWA used Compound-Specific Stable Isotope techniques to attribute the source of fine sediment in river systems (Gibbs & Woodward, 2018). They concluded that a substantial proportion of the sediment in the local region's rivers could be attributed to forest harvesting. Several articles in the Nelson Mail have reported these findings (Jones, 2018) in addition to coverage of the Cyclone Gita debris flow in Marahau (Sivignon, 2018), so forestry practices in the region are under the public spotlight. In order to preserve the plantation forestry industry's social licence to operate in the region, it is in the interest of forestry companies to take proactive steps to ensure that their operations follow best practice with respect to minimising sediment delivery to waterways.

2.2 SEDIMENT GENERATION AND DELIVERY

Sediment is generated by erosional processes acting on the soil. The four most common categories of erosion in New Zealand are surface erosion (including sheet, rill and wind erosion), gully erosion, mass-movement erosion and stream bank erosion (Basher, 2013). Mass movements are the generally the most significant contributors to sediment yields in New Zealand (Phillips, 2013), and plantation forest catchments are no exception (Marden, Rowan, & Phillips, 2006). Slope stability is reduced for two to six years following harvesting compared with other times in the forest growing cycle. This is termed the "window of vulnerability" (Phillips et al., 2012). This effect is due to higher effective rainfall reaching the soils than when the canopy was in place, and the net effect of reduced stabilising effects of the established mature root systems of the harvested crops due to decomposition, offset by increased stabilisation from the growing roots on the new crop.

The loss of physical root reinforcement and disturbance of the soil also increases its susceptibility to erosion (Phillips et al., 2012). Landslides (classified by Basher (2013) as mass movement erosion) are associated with significant triggering rainfall events. So, when and where landslides will occur has proven difficult to predict due to the stochastic nature of significant rainfall events and the many factors that underlie slope stability (Phillips, 2013). Therefore, the other forms of erosion are currently more able to be influenced by management practices to reduce sediment delivery to streams.

The most significant cause of sediment generation besides landslides is the surface erosion of exposed bare soil, from such harvesting related activities as extraction scarring (scalping), road and landing construction (earthworks), and machine tracking soil disturbance (Phillips, 2013). Forest roads have been found to be significant sources of sediment generation (Fahey & Coker, 1989; Fransen, 1998) although forest engineering has come a long way since those studies took place through the development and implementation of improved management practices. In a study by Marden et al. (2006) in Whangapoua Forest in Coromandel, soil disturbance of ridges caused by cable logging corridors (scalping) was the most significant contributor to sediment generation, while sheet erosion from bare soil in the cutover was found to be the smallest contributor to total sediment generation. Most sediment generated from bare areas is rapidly intercepted by the micro-topography and ground cover (e.g. slash or vegetation) (Phillips, 2013).

This highlights that the connectivity of on-slope generated sediment to stream channels is a vital concept for forest managers to understand to avoid or mitigate sediment delivery to streams. However, this connectivity has been identified as an aspect that is poorly understood in the older literature (Marden et al., 2006).

This gap in the literature was addressed by Brown & Visser (2017), who looked at the linkages between erosion sources and stream channels. The concept of a sediment breakthrough was used to describe the pathway of concentrated runoff and sediment that reaches a stream channel. They found that breakthroughs were primarily associated with roads, trails, and tracking (50%), and stream crossing approaches (23%). Within the areas studied by Brown & Visser (2017), there were 3.4 breakthroughs per kilometre of stream channel or 0.15 breakthroughs for every one hectare of harvest area. This study was conducted over a variety of soil types and harvest systems.

Many factors appear to influence sediment delivery (Amishev et al., 2014). The factors that influence sediment delivery can be classed into three categories. The first category is site susceptibility factors, including the slope steepness, the amount of ground cover/micro-topography, soil erodibility, and stream channel density. The second category is harvesting and earthworks factors, including quantity and proximity of earthworks to streams, harvesting methods (Marden et al., 2006), and sediment control features. The third category is climate factors that act on the site post-harvest including rainfall amount, intensity, and frequency (Amishev et al., 2014).

There is a shortage of research on which factors most significantly affect post-harvest sediment delivery, with a focus on concentrated sediment pathways across a common soil and terrain type. A study of this nature would increase the precision with which managers can make decisions to effectively avoid, mitigate and remedy negative environmental outcomes.

2.3 SOIL ATTRIBUTES OF THE MOUTERE GRAVELS

The study areas were situated in a geological area known as the Moutere gravels; a Pliocene-early Pleistocene colluvium sheet that fills the Moutere depression in the Tasman District (Basher & Jackson, 2002). Golden Downs Forest has been soil-mapped at a nominal scale of 1:50,000, with the data available via S-MAP (Landcare Research NZ Ltd, 2018). The soils in this area can be characterised as having slightly - moderately stony upper horizons and very stony subsoils, held together by weathered clays (Basher & Jackson, 2002).

The study sites in the Moutere gravel contain a mix of four soil families (Table 1), with each site containing a combination of these soil families, estimated with low to moderate confidence according to S-MAP. The relative ratios of soil family in each site are shown in Appendix 3.

Table 1: Key attributes relating to sedimentation potential for soil families in Golden Downs forest, according to S-MAP.

Soil Family	**Norris*f***	**Spooner*f***	**Kurunui*f***	**Donald*f***
Soil subgroup	Weathered Orthic Brown	Weathered Firm Brown	Acidic Orthic Brown	Acidic Firm Brown
Texture Profile	Loam over clay	Loam over clay	Loam over clay	Clay
Drainage class	Moderately well-drained	Well-drained	Well-drained	Well-drained
Hydrological Soil Class	Class A	Class B	Class B	Class B

The soil families of the Moutere gravels are Weathered and Acidic, Orthic and Firm Brown soils, which have a uniform yellow-brown subsoil colour (Stewart et al., 2004). These soil orders behave relatively similar in terms of their drainage and hydrological soil class; with moderate to well-drained ratings indicating that these soils are quick to drain excess water, and their hydrological soil class rating indicating that they have a very low to low (Class A or B) vulnerability to produce runoff (Landcare Research NZ Ltd, 2018). Concerning their land use capability classification, the study area is composed of 6e16 and 7e11 classes, which translates to low and moderate erosion susceptibility classes under the NES-PF (Ministry for Primary Industries, 2018). Overall, the soils of the Moutere gravels have a relatively low intrinsic sedimentation risk, especially when compared to other more erodible soils in the region such as the Separation Point Granites.

3 RESEARCH AIMS, QUESTIONS AND HYPOTHESES

3.1 RESEARCH AIMS

Nelson Management Limited seek to continue to improve their sedimentation performance. It was identified that describing the ground disturbance associated with common harvest systems and how these practices influenced sediment delivery would help managers to identify the sediment delivery risks for each system. Managers would get a clearer picture of where to focus on breaking hydrological connectivity between sediment sources and streams for each system. The study was to be conducted within a common terrain and soil type, the Moutere gravels, to ensure the findings were specific to their operations.

3.2 RESEARCH QUESTIONS

1. What are the typical soil disturbance patterns associated with each harvest system?
2. How do harvest system and site attributes influence sediment delivery risk on a common soil type?
3. Can supervised image classification of aerial photos be used to estimate bare soil percentage for harvest settings reliably?

3.3 RATIONALE

To answer the research questions, specific variables were selected, and research hypotheses formed. To answer Research Question 1, the site characteristics, soil disturbance and harvest systems were documented using field notes and photography. A basic image classification method was developed. This would allow the calculation of bare soil percentages and the creation of soil disturbance maps, which describe the spatial distribution of soil disturbance for each harvest setting. This process would generate a quantitative measure of the soil disturbance level. This method showed initial promise, comparing well against an "expert" interpreter, however, the reliability should be tested against a reliable ground survey method before the results can be presented with certainty. This reliability is tested in Question 3.

To answer Research Question 2, concentrated sediment breakthrough frequency was selected as the dependent variable for this investigation, to provide a quantitative measure of sediment delivery. Breakthroughs are identifiable sources of concentrated sediment delivery to streams. The dependent variables that were selected for this study as factors that influenced concentrated sediment breakthrough risk included mean site slope, stream length per ha, roading length per ha, extraction method and crew. Mean site slope was selected as a factor because slope was consistently found in the literature to be a significant influence on sediment delivery risk. The rationale for selecting stream length per ha was that it is a factor that is a measure of proximity of streams to cutover. From what is known about sediment delivery risk, it would make sense that the higher the density of streams in the harvest area, the higher the chance of sediment delivery to a stream. Roading density was selected as a factor, as this is a good metric of the quantity of earthworks per ha. Extraction method was selected as a factor due to the significantly different methods of stem extraction of the two methods. Crew was selected as a factor because each crew had its own system of specific machines that may have influenced the level of sediment generation differently. In addition, there may have been an effect of crews having consistently different environmental performance.

3.4 HYPOTHESES

The null hypothesis for the soil disturbance question (Question 1) is:

- There were no differences in soil disturbance patterns between sites, including slope tracking, roading and extraction scarring, related to different harvest systems.

The null hypothesis for the sediment delivery risk analysis (Question 2) is:

- There was no significant influence on sediment breakthroughs per ha by mean site slope, stream length per ha, roading length per ha, extraction method or crew.

The null hypothesis for the bare soil classification method analysis (Question 3) is:

- The bare soil classification method could not reliably estimate bare soil % for harvest settings.

4 METHODS

4.1 SITE SELECTION

This study took place in the Tasman District, New Zealand. In total 16 harvest settings were surveyed, of which 12 are located in Golden Downs Forest and four in the adjacent Kainui Forest (Figure 1), which share common soil characteristics as described in Section 2.3. The sites were stands of *Pinus radiata*, managed by Nelson Forests Limited. The number of sites observed was limited considerably by the following selection criteria:

- Hilly/steep terrain
- Common soil characteristics
- No site preparation or replanting
- Perennial or ephemeral streams within the operational boundaries.
- Must have experienced high rainfall conditions antecedent to sedimentation

Figure 1: Map showing the distribution of the study sites (blue) within the Tasman region

4.1.1 Antecedent Conditions

To control for climate effects on sediment delivery, settings which were most likely to have been affected by a significant rainfall event were identified. The date of harvest completion and of observation were compared to rainfall recorded at Wai-iti-Belgrove (Tasman District Council, 2018), to check whether the site had experienced weather conditions likely to trigger sediment runoff within this window. A significant rainfall event was assumed as either any single 24 hrs with > 50 mm rainfall or any month where the monthly total was at least double the average monthly total (Mark Bloomberg, personal communication, August 22, 2018).

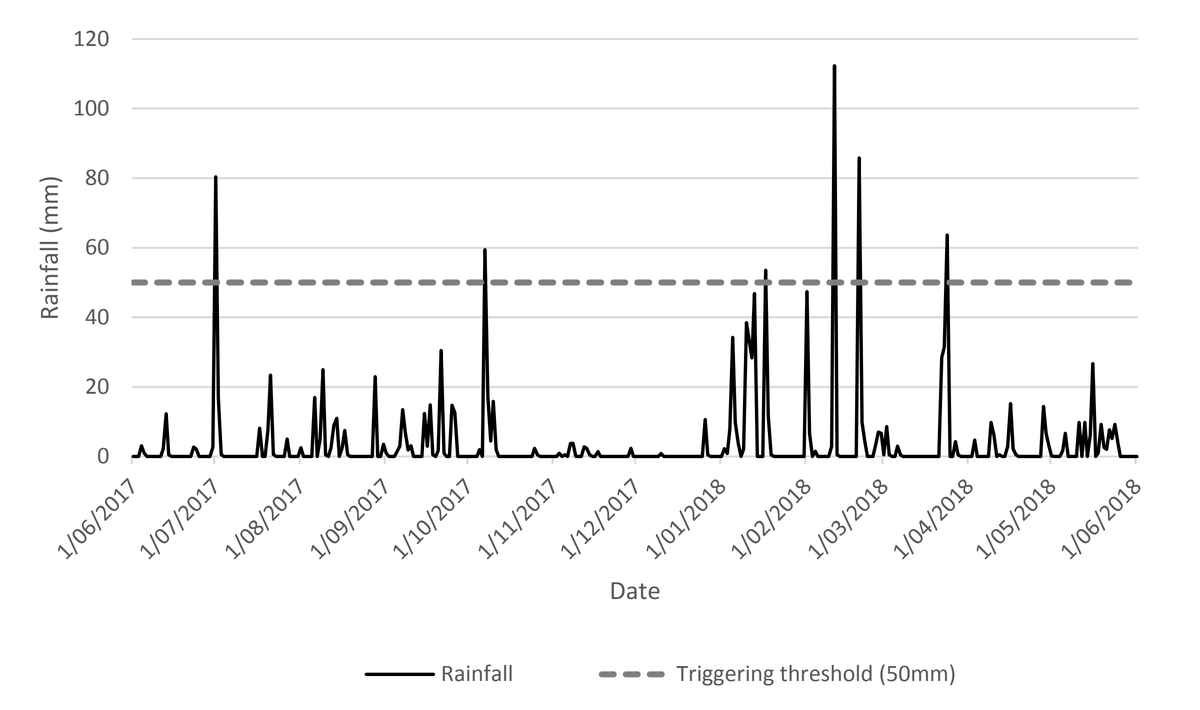

Figure 2: Daily rainfall quantities (mm) throughout June 2017 – June 2018 at Belgrove, with a line indicating the assumed triggering threshold for sediment breakthroughs.

The daily rainfall exceeded the triggering threshold on six occasions during the observed period, with the maximum rainfall of 112 mm of rainfall occurring during Cyclone Gita on the 11th February 2018. There was a conspicuous absence of rainfall between mid-October 2017 and mid-January 2018.

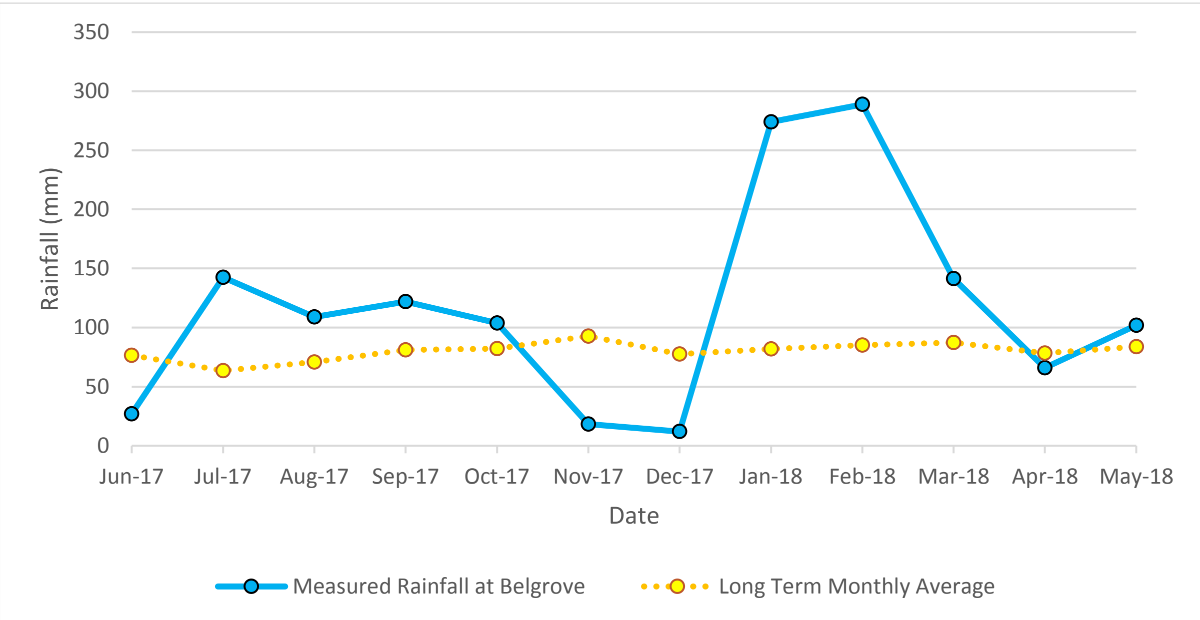

Figure 3: The average monthly rainfall quantities (mm) over the period from June 2017 to June 2018, along with the long-term average monthly rainfall (mm).

For monthly rainfall (Figure 3), July 2017 saw quite a wet winter with 142 mm of rain falling, which was double the monthly long-term July average for the area. There was also a significant wet period over the January-February period, due partly to the high rainfall of ex-cyclone Fehi and cyclone Gita. Several sites observed throughout November and December had not had enough rainfall to trigger sediment breakthroughs, so had to be excluded from the final data.

4.2 THE HARVEST SYSTEMS

4.2.1 Ground-based

Three crews harvested the five ground-based sites; with crew A and crew F harvesting two settings each, and crew E one setting (Appendix 3). The ground-based logging systems used for these five sites typically consisted of mechanised felling machines performing the felling component and shovelling, and a grapple skidder performing the primary extraction.

4.2.2 Cable yarder

The four cable yarder sites were harvested by 11 crews; with crew C harvesting four settings, crew E harvesting three settings, and crews B & D harvesting two settings each (Appendix 3). The cable yarding systems used for these sites included both tower yarder using a high-lead rigging system, and swing yarders using a mechanical grapple. Two of the four high lead settings were felled manually, while all other settings were felled using a mechanised felling machine. Bulldozers and specifically designed machines were used as the tail-holds. The decision to combine the swing yarder and high lead harvest systems into one cable yarding category was made because there were limited data from each of the systems, but these systems share many common characteristics allowing for a distinct comparison with ground-based systems.

It should be noted that some crews experienced breakdowns, meaning that although they were primarily a yarder-based crew they had to ground-based log some sites, which would not represent their normal practices.

4.3 DATA COLLECTION

Harvested settings were surveyed over the period of December 2017 – April 2018. Data collection involved a combination of field survey and image analysis. Sediment breakthrough frequency and the soil disturbance patterns were assessed for 16 harvest settings, with two harvest systems and six crews (Appendix 3). Of the many factors to consider when attempting to observe sediment breakthrough frequency, the factors that was considered in this study were mean site slope, extraction method, crew, roading density and stream length per ha.

For each setting, the operational area was defined by using a shapefile of the setting boundaries in combination with field observations to capture the full extent of soil disturbance associated with the harvesting process. Field mapping and measurement was carried out using the Avenza maps version 3.3.3 for iPad (Avenza Systems Inc., Toronto, ON M4S 1A1, Canada).

Perennial and ephemeral streams were identified using digital elevation models, together with field inspection to verify that they showed evidence of concentrated flow. The lengths of these water bodies were walked, documenting breakthroughs and their sources as per the methods used by Brown & Visser (2017). A combination of ortho-rectified aerial photo-mapping, field observation and Digital Elevation Models (DEMs) was used to measure the length of waterways and skid roads, a method like that used by Talbot, Rahlf, & Astrup (2018). Mean site slope was also derived from a DEM.

It was decided that the most time and cost-efficient way to create bare soil maps and estimate bare soil percentages for the 16 harvest settings was to perform an interactive supervised image classification using recent ortho-mosaics. However, the reliability of this method was untested, so the results had to go through a validation process to ensure they were representative.

The aerial photos were taken from a fixed-wing aircraft. These photos had a pixel size of 0.74 m and were ortho-rectified using Agisoft Photoscan (Agisoft LLC, St. Petersburg, Russia) and geo-rectified to 10 m accuracy. The interactive supervised image classification tool on ArcGIS 10.4.1 (ESRI, Redlands, CA, USA) was used to perform a maximum likelihood classification to categorise the cells of the aerial image raster as bare or covered soils. For training samples, an area of homogeneous bare soil (skid site) and an equal-sized area of homogeneous covered soil were marked using GPS in the field. These training areas were approximately 30 m^2 per hectare of cutover for each site. This tool considered the variance and the covariance of each of the training sample class signatures assuming a normal distribution of the class sample, and assigned each raster cell in the image to one of the two classes based on the highest probability of being a member (ESRI, 2018).

This method required evaluation to quantify its reliability. To validate the accuracy to the supervised classification procedure, the method was compared to a reliable ground survey method. Due to time constraints and land preparation operations commencing, the original 16 settings could not be resurveyed. Instead, the image classification method was repeated and compared to ground survey at Blackbird Valley Forest in the Tasman District over three days.

The method of ground survey used was based on the point transect method, based on the method described by McMahon (1995). Nine 1 ha plots were surveyed, with transects placed at 25 m intervals and measurements taken at 1 m intervals perpendicular to the primary slope. This ensured that there was an approximate 5% absolute error associated with the observations. Points were categorised as bare" or "covered" soil. The boundaries used for each plot were easily distinguished physical boundaries such as spurs and waterways.

4.3.1 Soil Disturbance Categories

Roads

The roads category included earthworks related to spur road and skid trail construction. These were a benched surface that was engineered to be used repeatedly by vehicles. Sometimes these roads had been closed by "pulling back" the fill slopes post-harvest. Excluded from the category were primary roads used by trucks for log haulage. These were located outside the setting which the operational area was based upon. Skid sites and their associated sediment management features were also excluded from the operational area.

Parts of Golden Downs and Kainui forests have experienced three or four rotations, so legacy roads and benches are littered across the landscape. These were included in the "roads" category because often these benches were used repeatedly by machinery despite no upgrade.

Slope Tracking

This category included unbenched soil disturbance paths on the slope, created by a skidder/felling machine/tail-hold machine. This category also included any visible rutting from the tracks and slips caused by the slope tracking where the machine had sat while working on the slope.

Extraction

The extraction category included all sediment generated from soil disturbance associated with the extraction of stems from the site to a skid. It included hauler corridor scars, scalped ridges and exposed soil areas resulting from shovel logging.

Unknown

This category was used where there was no identifiable harvesting or earthworks source for the sediment breakthrough. These were particularly erodible parts of the hillslope from which shallow land-sliding had generated sediment.

4.3.2 Sediment Breakthroughs

Stream

Streams were identified as entrenched dry gullies where concentrated overland water flow occurs from time to time (ephemeral), or year-round (perennial). In the observed sites, only ephemeral streams were actually present.

Sediment Breakthroughs

A breakthrough was assessed as a location where concentrated runoff or sediment connected with a stream. For field observations, this was where there was direct evidence of a sediment flow entering a stream from an identifiable cause.

4.4 DATA ANALYSIS

The descriptive statistics were conducted using Microsoft Excel. The statistical program R was used to conduct the linear regression analysis. The threshold for significance was $\alpha = 0.05$, where p-values ≤ 0.05 were considered significant. The dependent variable for the sediment breakthrough frequency prediction analysis was sediment breakthroughs per ha, because this measure of breakthrough frequency corrects for the effect of setting size on the stream length per setting (Table 2), and the units were more consistent with the roading density and stream density predictor variables which were both measured on a per hectare basis. The factors considered were mean site slope, extraction method, crew, roading density and stream length per ha. These factors are a mix of categorical and continuous variables. Before fitting the first model, the factors were tested for collinearity, with variance inflation factors produced for each variable.

Due to the small sample size, a graphical analysis was used to interpret the results of the analysis, to identify any patterns that could indicate that the low power of test could have resulted in type 2 errors, which could warrant further investigation in future studies.

For the reliability assessment of the bare soil image classification method, the results of the ground survey were correlated against the results from the image classification at the transect level.

5 RESULTS

This section presents a description of some of the observed characteristics of the sites that relate to soil disturbance and sediment delivery risk and are summarised by harvest system category. Site characteristics were assessed for their relationship with sediment breakthrough risk for each system, and the observed soil disturbance was characterised. The site and harvest system factors that were thought to influence the sediment breakthrough frequency were statistically evaluated. Finally, the bare soil classification method that was developed to rapidly create bare soil maps and calculate site bare soil percentage was assessed for its reliability.

5.1 SITE CHACTERISTISICS

This study observed a total of 164.5 ha of harvested area, and 7.6 km of stream channel (Table 2), all of which was ephemeral. Harvest settings were very topographically variable. Summaries of these physical characteristics are shown by extraction system (Table 3).

Table 2: The total area (ha) and stream length (km) observed in this study, by extraction system.

	Cable yarder	**Ground-based**
Settings (N)	11	5
Total Area (ha)	119.2	45.3
Total Stream Length (km)	4.9	2.7

This study observed 11 cable yarding sites and only five ground-based sites. Subsequently, there was substantially less cutover area and stream length surveyed for ground-based sites. On average, the cable logged sites were 1.7 ha larger. Also, cable logged sites were on average steeper than ground-based sites, with an average slope of 25.8 degrees compared to 21.5 degrees, which is to be expected from a harvest system selection perspective.

Table 3: Site characteristics summarised by extraction method, including area, stream length, stream density, site slope and road density.

** mean, ** weighted average on a spatial basis.*

	Cable yarder			Ground-based		
Factor	**Average**	**Min**	**Max**	**Average**	**Min**	**Max**
Site area (ha)	10.8*	4.19	21.21	9.1*	4.68	13.5
Site stream length (m)	447*	25	479	534*	240	1225
Stream density (m/ha)	41.2**	8.68	71.5	58.9**	45.8	147.9
Site slope (degrees)	25.8**	19.9	28.4	21.5**	16.6	27.3
Roading density (m/ha)	45.4**	0	170	109.4**	33.3	179

The average stream density was 43% higher for ground-based sites, suggesting that there may be a higher risk of sediment delivery in the ground-based sites since sediment delivery depends on access to a waterway. There was also a substantial difference in roading density, with ground-based sites having 2.4 times the roading density of cable logging sites.

5.2 SEDIMENT DELIVERY BY HARVEST SYSTEM

The observed sediment breakthrough spatial frequencies are summarised in Table 4, with a full table of breakthrough frequencies by site provided in Appendix 1. There were no perennial streams within the observed harvest areas, so all sediment breakthroughs were into ephemeral stream channels.

Overall, 51 separate breakthroughs were observed. Settings logged using cable yarding machinery saw 26 breakthroughs across 11 sites, with a median value of two breakthroughs per site. Settings logged using ground-based methods saw a total of 25 breakthroughs over five sites, with a median number of six breakthroughs per site.

The breakthrough frequency per stream kilometre was 71% higher for ground-based sites, compared with cable logged sites (Table 4). On a per hectare basis, the trend was the same, with ground-based breakthrough frequency per hectare 139% higher than cable logged sites.

Overall, there were weighted average breakthrough frequencies of 6.86 per km of stream channel and 0.31 per ha of harvest area. The variability of the breakthrough frequencies can be seen in Appendix 1, with the ranges of frequencies for ground-based encompassing 0.01 – 12.35 per km and 0.15 – 0.85 per ha, and the ranges for cable yarder encompassing 0.00 – 22.73 per km and 0.00 – 0.45 per ha. There is large variability in breakthrough frequency between sites with a common harvest system.

Table 4: The observed sediment breakthrough frequency by extraction method.

	Cable yarder	**Ground-based**	**Total**
Breakthroughs observed	26	25	51
Breakthroughs per stream km	5.29	9.37	6.86
Breakthroughs per ha	0.22	0.55	0.31

The causes of these sediment breakthroughs were broken down into categories for each harvest system type (Table 5). The most significant source of sediment breakthrough for cable yarder sites was from tracking on the slope, while skid and spur roads were the primary source for ground-based sites. 11% of cable yarder breakthroughs had an unknown source, meaning that their cause could not be attributed to any form of harvesting or earthworks related soil disturbance. For ground-based sites, the primary cause of sediment breakthroughs was from concentrated runoff from skid tracks and spur roads which made up 60% of the observed breakthroughs. A further 24% were from tracking on the slope and 16% from extraction related disturbance.

Table 5: Ground-based and cable yarder sediment breakthrough causes and their relative frequency.

	Cable yarding		**Ground-based**	
Cause	**N**	**%**	**N**	**%**
Slope Tracking	16	62	6	24
Roads	5	19	15	60
Extraction	2	8	4	16
Unknown	3	11	0	0
Total	26	100	25	100

For both systems, the vast majority of sediment breakthroughs resulted from some form of harvesting related soil disturbance, particularly from earthworks and deep scarring from machine tracks on the slope.

5.3 CHARACTERISATION OF SOIL DISTURBANCE

This section had intended to report site bare soil percentage values and describe the spatial distribution of soil disturbance from maps produced by image classification by harvest system. However, the reliability of the image classification procedure was found to be insufficient (Section 5.5), so this characterisation relies upon field notes and photo examples.

Generally, the impression of the environmental outcomes of these harvested sites was positive. The majority of the sites observed showed that company policy had been followed as per NMLs Environmental Management System. There were, however, some notable examples that help illustrate where practice could be improved to avoid, mitigate or remedy sediment delivery to streams.

For cable logged sites, soil disturbance was typically confined to scalped ridgetops (Appendix 5). The soil disturbance could generally be characterised as extensive areas of shallow disturbance that did not expose B horizon soil. The two instances where cable extraction did result in sediment breakthrough occurred on small areas of steep “blind” slopes along the extraction corridors, where the disturbance from the dragging of logs over the soil was enough to cause the soil to erode.

For ground-based sites, as previously stated, the most common source of sediment breakthrough was from spur roads and tracks. The majority of these breakthroughs were at ephemeral stream crossings, where large areas of bare soil were exposed allowing sediment to flow towards the stream channel (Appendix 7).

Often, visually striking disturbances in the cutover did not contribute to sediment breakthroughs (Appendix 4). Factors that appeared to distinguish machine tracking disturbances that delivered sediment to streams from those that did not, included greater distance from waterways and increased ground cover.

5.3.1 Specific Examples of Sediment Delivery

To help illustrate the findings of Section 5.2, some specific examples of critical areas to address are described. These include not adequately closing out skid trails or deep machine track disturbance, roads located very close to stream channels, extracting through stream channels and crews deliberately discharging sediment into streams.

In setting N713_2, a skid trail fill slope was located within 5 m of an ephemeral stream at multiple points. Sediment control features had been installed correctly, but due to the proximity to the stream channel the sediment could not be dispersed but was instead concentrated into the stream channel. Given this is not a perennial waterway, this is not contrary to rules in the NES-PF but could have been avoided with better road placement.

Failure to close-out skid trails and deep machine tracking disturbances immediately post-harvest was another notable source of sediment breakthrough. Skid trails were routinely "pulled back" post-harvest, but at setting N811_3, the crew had not pulled back the entire skid trail, leaving the trail exposed without any sediment control features and leading to a sediment breakthrough further downslope. A post-harvest inspection had not yet been carried out by the planner. In another example, at setting N807_3, two tail-hold machine tracks had been made downslope towards an ephemeral stream without cut-outs or slash cover to catch or disperse runoff, leading to some rilling which resulted in sediment breakthrough (Appendix 6).

Setting N713_15 saw shovel harvesting of stems into an ephemeral stream channel. The setting was originally planned to be harvested using a swing yarder, but due to hauler breakdown, it was decided by the planner that harvesting could be completed by ground-based extraction, using primarily shovel logging of stems to the base of the site (Appendix 8). At the base of this site there was an ephemeral stream, from which the stems were pulled. This downslope shovelling caused disturbance of an old bench that ran parallel to and 5 m above the stream, contributing to four of the six observed breakthroughs on the site.

In setting N713_2, there was an incident of a discharge of sediment into an ephemeral stream from a skid trail by the harvest crew (Appendix 9). It appeared that the skid trail had become saturated and excessively muddy, so the crew had decided to discharge the sediment down the slope. The large mass of sediment flowed directly into an ephemeral stream channel.

5.4 FACTORS INFLUENCING SEDIMENT DELIVERY

Site and harvest system factors that are thought to influence the sediment breakthrough frequency are statistically evaluated in this section. This is done using linear regression where breakthroughs are the response variable, with a set of candidate explanatory variables including slope, stream length per ha, extraction method, roading density and crew.

5.4.1 Initial Model Selection

Before fitting a linear regression model, the independent variables were checked to ensure there was no collinearity. The variance inflation factors for all predictors were classed as low to moderate, but all were <10 so collinearity is not considered a problem (Table 6).

Table 6: A variance inflation factor table output from R, confirming none of the predictor variables are highly correlated.

Factors	GVIF	Df	GVIF^(1/(2*Df))
Mean Site Slope	19.98	1	4.47
Stream length per ha	1.87	1	1.37
Extraction Method	16.01	1	4.00
Crew	135.58	5	1.63
Road length per ha	1.75	1	1.32

The output in Table 7 shows the results of the full model (Model A), which specifies sediment breakthroughs per ha as a function of all the potential predictor variables: extraction method, roading length per ha, stream length per ha, mean site slope and crew. None of the predictor values shows significance at the $p \leq 0.05$ significance level, although extraction method shows significance at the $p \leq 0.10$ significance level.

Table 7: The regression output from R for Model A, sediment breakthroughs per ha as a function of extraction method, roading length per ha, stream length per ha, mean site slope and crew.

Factor	Df	Sum Sq	Mean Sq	F-value	p-value
Mean site slope	1	0.03527	0.03527	0.3689	0.5659
Stream length per ha	1	0.19442	0.19442	2.0335	0.2038
Extraction method	1	0.43574	0.43574	4.5574	0.0767
Crew	5	0.53337	0.10667	1.1157	0.4408
Roading density (m/ha)	1	0.00276	0.00276	0.0289	0.8706
Residuals	6	0.57367	0.09561	-	-

From this sample of harvest sites; the slope, crew and roading length per ha factors were not found to be significant predictors of sediment breakthroughs per ha. Using a process of backwards selection, the least promising predictor variables seen in Model A (mean site slope, roading length per ha, and crew) were dropped from subsequent models.

Model B specified sediment breakthroughs per ha as a function of extraction method and stream length per ha. The output from this model is shown in Table 8. By removing some of the factors that did not meet the $p \leq 0.05$ significance level in Model A, extraction method achieved a p-value of 0.0481, which is considered marginally significant. Stream length per ha still does not reach the required significance level of $p \leq 0.05$.

Table 8: The regression output R for Model B, sediment breakthroughs per ha as a function of extraction method and stream length per ha.

Factor	**Df**	**Sum Sq**	**Mean Sq**	**F-value**	**p-value**
Stream length per ha	1	0.22957	0.22957	2.6253	0.12916
Extraction method	1	0.40891	0.40891	4.6763	0.04981
Residuals	13	1.13676	0.08744	-	-

Model C was sediment breakthroughs per ha as a function of just extraction method. This simple model saw extraction method as the only significant predictor of sediment breakthrough frequency, with a p-value of 0.02183 (Table 9).

Table 9: The regression output from R for Model C, sediment breakthroughs per ha as a function of extraction method and, stream length per ha.

Factor	**Df**	**Sum Sq**	**Mean Sq**	**F-value**	**p-value**
Extraction method	1	0.57191	0.57191	6.6538	0.02183
Residuals	14	1.20333	0.08595		

The coefficients of Model C are shown below in Table 10. The adjusted r^2 of 0.2737 for this model is low, leaving much of the variability unexplained. The estimate for cable yarding is equal to 0.25 breakthroughs per ha, and the estimated frequency for ground-based operations is 6.66 breakthroughs per ha. The variability associated with these estimates is plotted in Figure 4.

Table 10: Linear regression output from R, showing the coefficients of Model C.

Coefficients	**Estimate**	**Std Error**	**T-value**	**Pr(> | t |)**
Extraction method – Cable yarder (intercept)	0.2509	0.0884	2.838	0.0131
Extraction method – Ground-based	0.4079	0.1581	2.58	0.0218

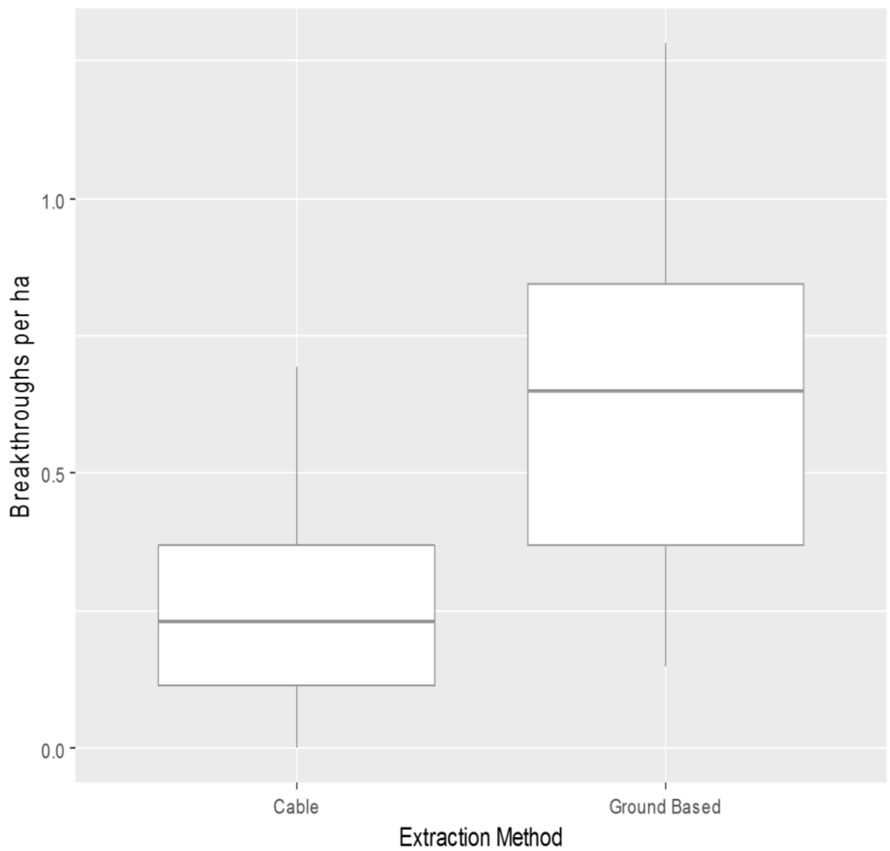

Figure 4: Boxplot of breakthroughs per ha by extraction method; the only significant ($p \leq 0.05$) predictor of sediment breakthrough frequency on a per hectare basis.

5.4.2 Testing for Linear Model Assumptions

Before making inferences from the best linear regression model, it is critical to determine whether the necessary model assumptions are valid. Diagnostic plots for Model C are shown below in Figure 5. The residuals vs fitted plot shows that the residuals are relatively homoscedastic, and the normal Q-Q plot shows that the residuals are approximately normally distributed. However, according to the residuals vs leverage plot, there does appear to be a significant influence of one of the data points on the model fit.

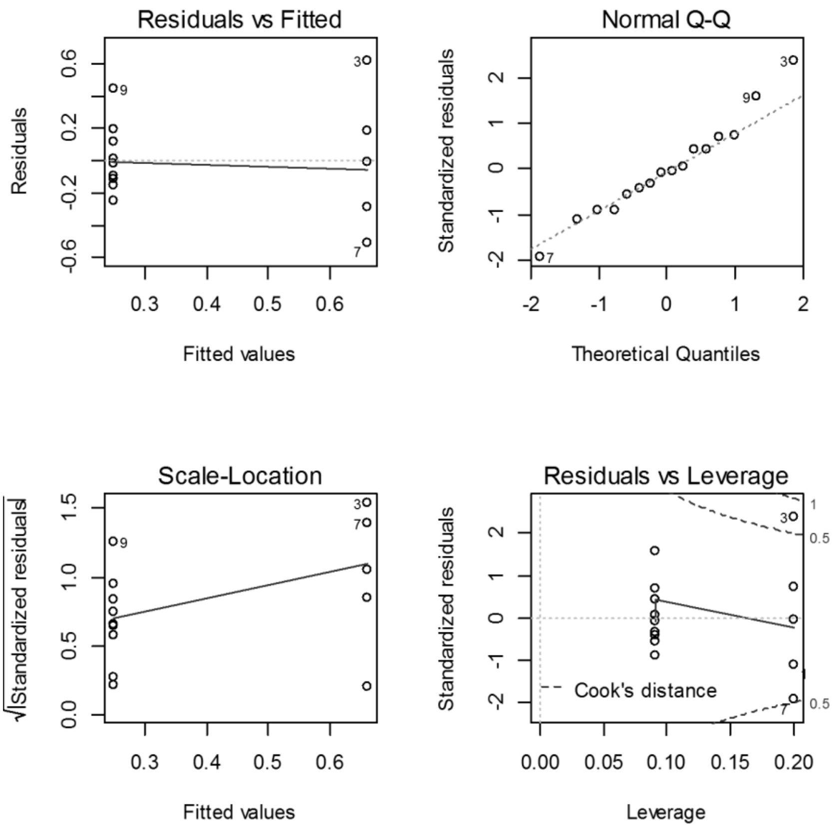

Figure 5: Statistical diagnostic plots for Model C produced by R.

Figure 6 graphically shows the relationship between breakthroughs per ha and roading density for cable and ground-based extraction methods. The fitted lines represent non-significant relationships, however, there is a significant outlier that causes a large leverage effect on the ground-based extraction line. Judging by the distribution of the data points, if this outlier was removed, it may reveal a significant influence of roading density on breakthroughs per ha. This outing data point is setting N713-15, which has six breakthroughs over its 4.68 ha extent

(Appendix 8). When breakthrough frequency is plotted against road length per ha, this setting is again a significant outlier, which has a high leverage on the relationship of ground-based extraction and roading density.

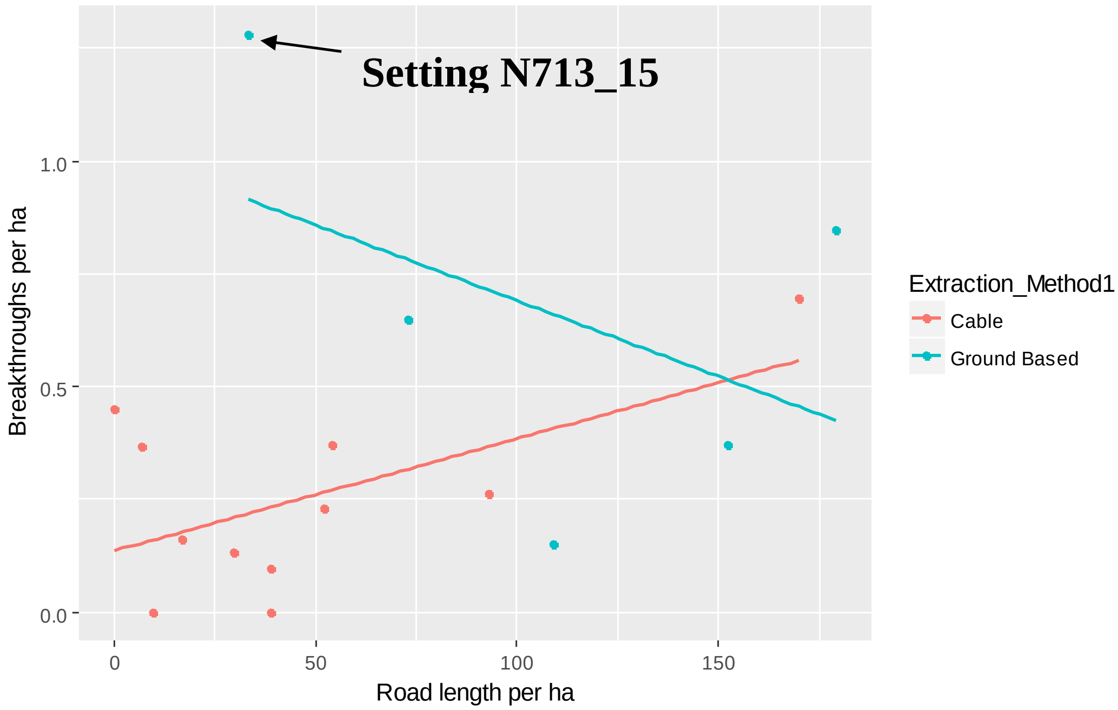

Figure 6: Scatterplot showing the relationship between breakthroughs per ha and roading density (m per ha), by extraction system.

As previously mentioned in the observations section, what differentiated this site from the other ground-based sites is that extraction was performed using shovel-logging, with minimal roading infrastructure to facilitate extraction. This site was initially planned to be cable yarded, but a hauler breakdown meant ground basing the site was an alternative option. This dissimilarity in the extraction method provides an apriori basis for exclusion of this outlier.

5.4.3 Alternative Model

The alternative model, Model D, was backwards selected from the full model; this time with exclusion of the outlier. Model D has only roading length per ha as a significant predictor variable ($p = 0.01297$) and with an r^2 of 0.324 explains a slightly higher proportion of the total variation than Model C (Table 11), but overall the model is still a relatively weak fit. Extraction method was no longer found to be a significant predictor when the outlier was removed leaving just four ground-based observations.

Table 11: The regression output from R for Model D, sediment breakthroughs per ha as a function of roading length per ha.

Factor	**DF**	**Sum Sq**	**Mean Sq**	**F-value**	**p-value**
Roading density (m/ha)	1	0.35174	0.35174	8.2767	0.01297
Residuals	13	0.55247	0.0425	-	-

What this model shows is that there is a significant positive linear trend in the predicted frequency of breakthroughs with increasing roading density of a harvest setting. The regression coefficients for Model D are shown below in Table 12.

Table 12: Linear regression outputs from R, showing the coefficients for Model D.

Coefficients				
Factor	**Estimate**	**Std. Error**	**t value**	**Pr(>|t|)**
(Intercept)	0.13754	0.082301	1.671	0.119
Roading Density (m/ha)	0.002646	0.00092	2.877	0.013

The equation for this relationship was:

Breakthroughs per ha = 0.002646(Road density (m/ha)) + 0.13754

The diagnostic plots (Figure 7) for Model D show that the residuals are relatively homoscedastic and unbiased and conform relatively well to the normality assumption despite a slight sigmoidal curve around the normal Q-Q fitted line. This time, there were no significant outliers in the data that exceeded Cook’s distance in the residual vs leverage plot.

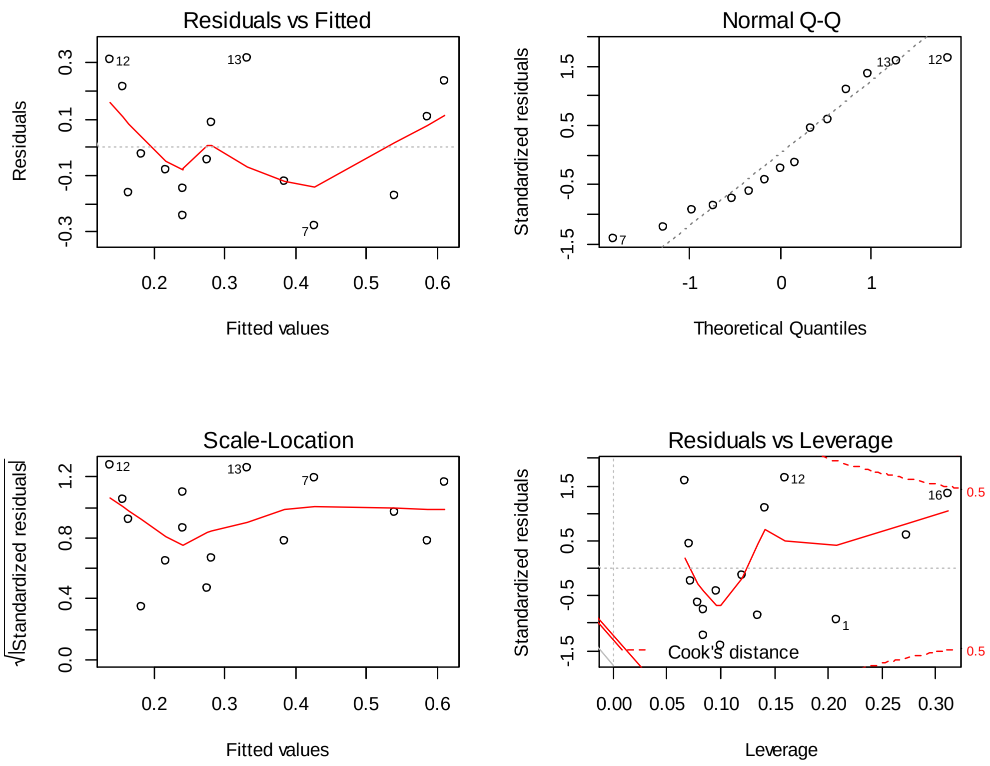

Figure 7: Statistical diagnostic plots for Model D produced by R.

5.4.4 Examining the Non-Significant Variables

Due to the small sample size, with only 15 settings included in the final model, the power of test may be quite low resulting in type 2 errors that reduce the ability of the analysis to detect significant influences of the predictor variables. However, using graphical analysis, some trends can be identified and compared with qualitative field observations.

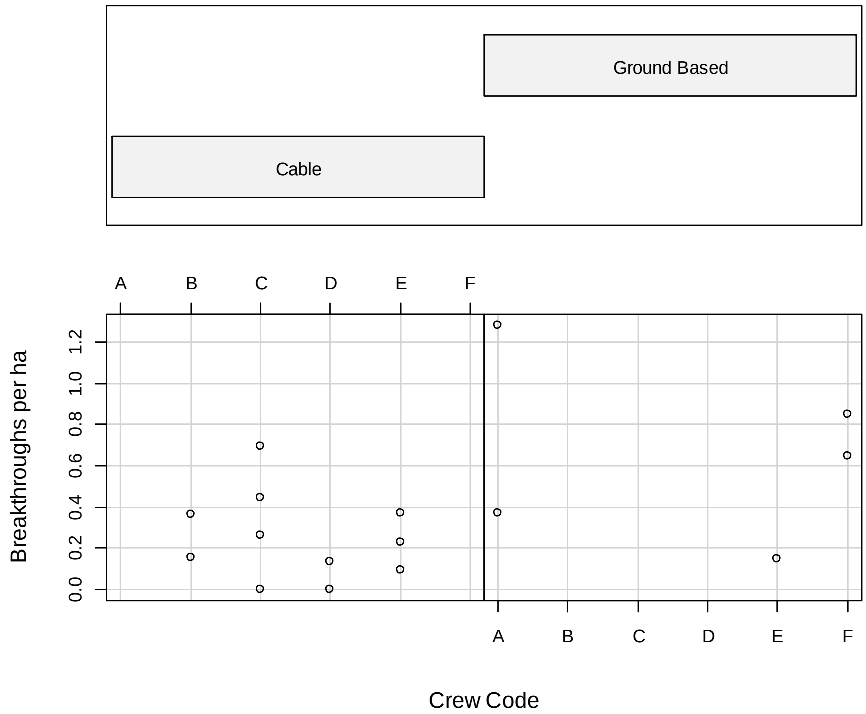

Figure 8: Plot showing the breakthrough frequency breakthroughs per ha (distributions) of crews.

As mentioned previously in the field observations, some crews appeared to perform practices that gave a subjective impression of increased sediment delivery risk. If the crew factor was to have a significant influence on sediment breakthrough frequency, we would expect to see small within-crew variation and large between-crew variations. Figure 8 shows the distribution of breakthrough frequency by crew. While there are differences among crews, there is not enough replication in the data to be able to infer any influence of crew on breakthrough frequency.

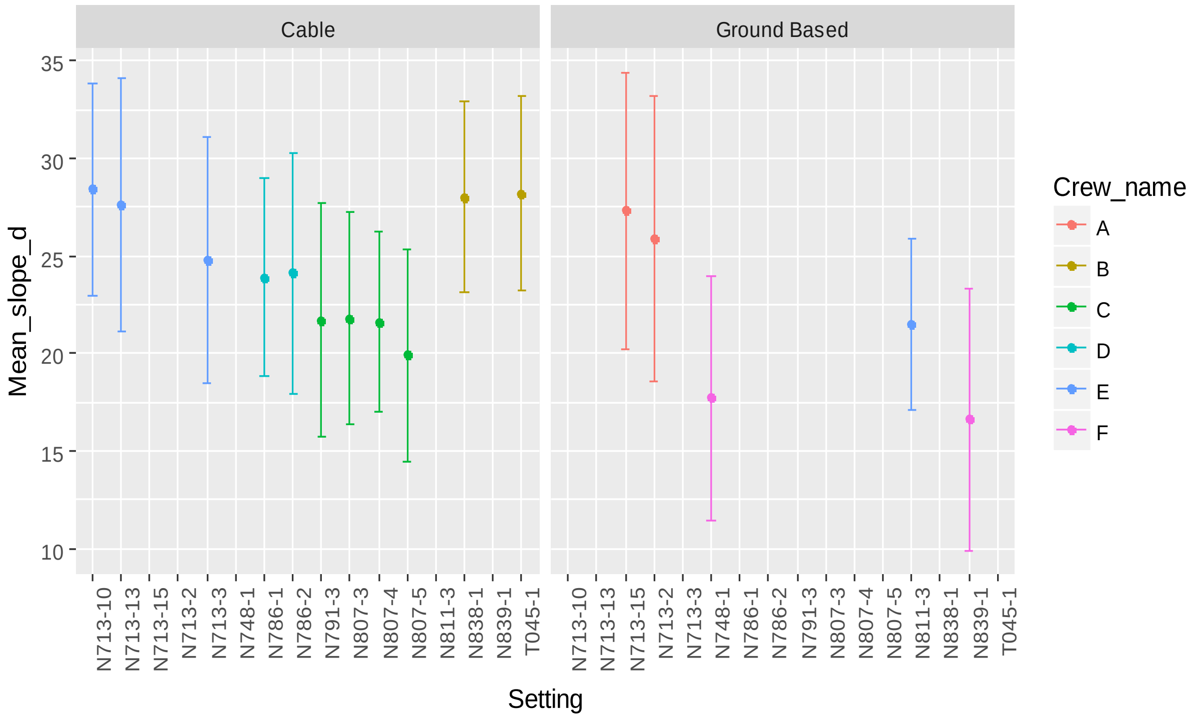

Figure 9: Mean setting slope in degrees (Mean_slope_d) with slope standard deviations represented by error bars for each harvest setting. Crews are represented by colours.

Mean site slope was not found to be a significant predictor of sediment breakthrough frequency. However, the mean slope may not have captured the effect of the steeper slopes within the site which may have contributed more to sedimentation risk. The mean slopes of each setting were plotted with their slope standard deviations (Figure 9), to see if site slope variability was potentially a more important driver than mean slope. However, the standard deviations of site slope did not differ drastically between sites, so it is unlikely to have altered the ranking of sites according to the mean slope.

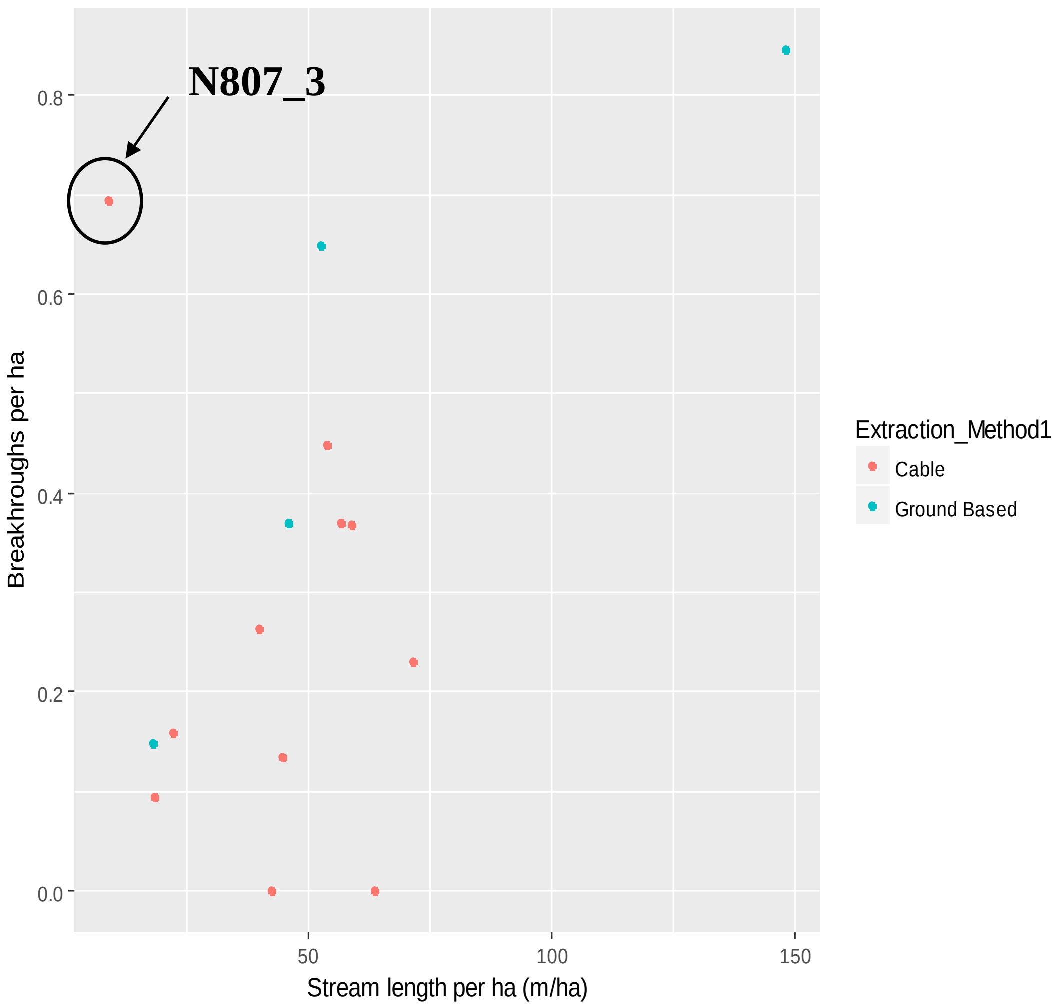

Figure 10: Scatterplot showing breakthroughs per ha by stream area ratio.

There was no significant relationship found between stream length per ha and breakthroughs per ha. It was hypothesised that a higher stream density would make a site more susceptible to sediment breakthroughs, but this is not borne out by the data. The data point that seems to deviate markedly from a positive linear relationship is from setting N807_3, which has been verified to be a legitimate and accurate value. This was a 2.9 ha head of a gully with a very short section of ephemeral stream channel within the setting boundary resulting in a very low stream length per ha (Appendix 6).

5.5 BARE SOIL PERCENTAGE RELIABILITY

The reliability of the aerial image classification method was assessed using a comparison to a reliable ground survey method. Figure 11shows the relationship between the results of the ground survey against the predicted value produced by the image classification method.

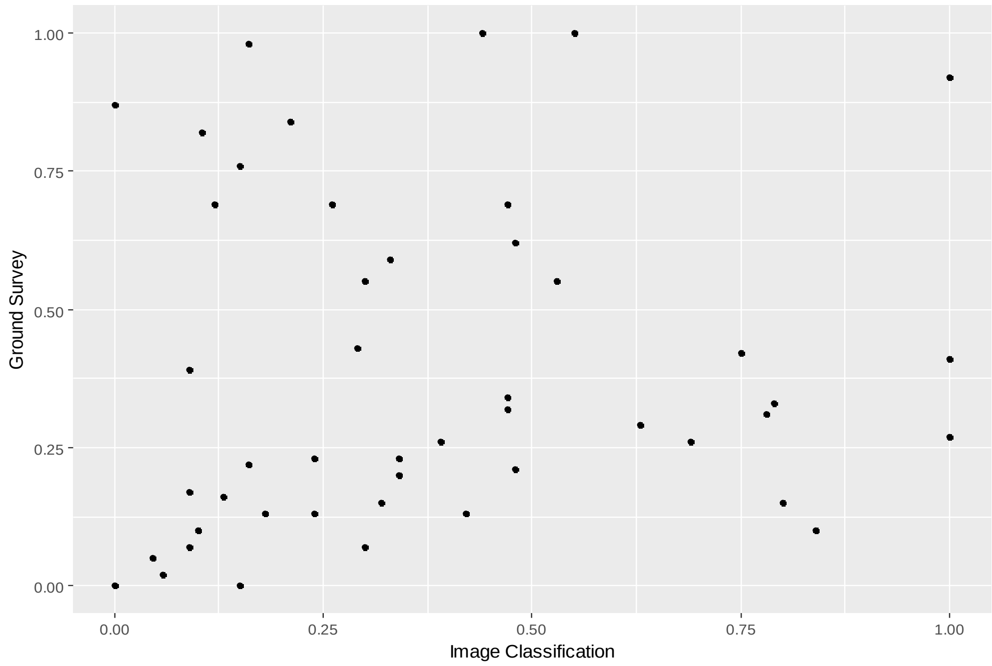

Figure 11: Scatterplot showing the bare soil % estimation from image classification against the bare soil % estimation from ground survey for each transect. 9 plots, (N= 48)

The evaluation process showed there was very little correlation (R = 0.1176) between the two classification methods (Figure 11). The bare soil percentage values that were estimated from image classification for each site individually could not be used to quantify the extent of site soil disturbance because the method failed to be proven reliable. An example of a reliability assessment plot is shown in Figure 12.

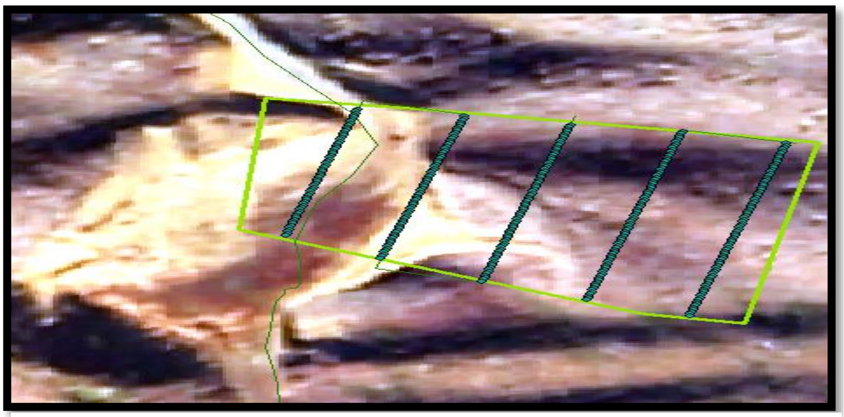

Figure 12: Example section of an aerial photo used to assess the reliability of the bare soil image classication method, with a validation plot containing five transects at 25m spacing, overlaid on top of a skid site and cutover. The photo shows signiifcant shading effects.

6 DISCUSSION

6.1 SOIL DISTURBANCE PATTERNS

One objective of this study was to observe whether there were soil disturbance patterns associated with each harvest system, and to describe these patterns to understand the sediment generating processes. Since the bare soil image classification technique was not found to be reliable, this section had to rely on using field note and observations. It was observed that there were significant differences in soil disturbance patterns between sites. Cable yarder sites generally showed minimal soil disturbance, but when deep soil disturbance that produced bare soil did occur, it was isolated to the ridge tops, far from stream channels. In comparison, the ground-based sites had significantly more deep disturbance in closer proximity to stream channels from roading earthworks.

6.2 SEDIMENT BREAKTHROUGH FREQUENCY

6.2.1 Observed Breakthrough Frequency

The sediment breakthrough frequency observed at ground-based sites was significantly higher than cable yarder sites. The overall frequency of sediment breakthrough by stream length was 50% higher than the frequency found by Brown & Visser (2017), and the frequency of breakthroughs by harvest area was also higher by 61%. For cable yarding sites on average, a breakthrough was found every 190 m of ephemeral stream or every 4.55 ha of harvest area, compared to every 270 m or 7.14 ha. For ground-based sites on average, a breakthrough was found for every 107 m of ephemeral stream or for every 1.82 ha over harvest area, compared to every 134 m or every 2.63 ha.

Across all sites, sediment breakthroughs were almost entirely associated with some form of forest harvest activity; including roading, stem extraction or slope tracking disturbance. The natural soil characteristics of the Moutere gravels predispose them to low risk of mass movement erosion, and this is shown by only two of the 51 breakthroughs found to not be due to harvesting or earthworks related soil disturbance. For cable logged sites, tracking on the slope was the primary source of generated sediment that was delivered to streams, with 16 of the 26 breakthroughs. For ground-based sites, roads were the primary sources of sediment breakthrough, contributing to 15 of the 25 breakthroughs. Together, these two disturbance categories contributed to 82.4% of all breakthroughs.

Extraction scarring that resulted in the scalping of the ridge tops did not show signs of connectivity to streams, thus although there appeared to be a large amount of sediment generated, this was dispersed into the cutover rather than being concentrated towards waterways.

None of the breakthroughs observed in this study was delivering sediment to perennial streams. The significance of this concentrated fine sediment delivery to ephemeral streams to downstream water quality was not considered in the scope of this study. Further study on the rate that this sediment is transported to perennial waterways would be of importance to understand the significance of sediment transport to ephemeral streams in the Moutere gravels aura.

Being able to identify sediment breakthroughs in the field is a relatively subjective process, so despite the clear definitions used to assist identification, there will be some variation dependant on the observer. Definitions of disturbance types and connections are quite difficult to categorise, as there are many forms that connectivity can take. The development of a consistent framework of definitions and photographic examples to identify different forms of breakthroughs would be beneficial for future studies and managers.

6.2.2 Factors Influencing Sediment Breakthroughs

When attempting to account for some of the site and system factors that were thought to influence sediment delivery, the results of the regression analysis showed that for the Moutere gravels, the best predictor of sediment breakthrough frequency was roading density. Given that the literature has suggested that these chosen predictors were likely to have significant influences on breakthroughs, it was interesting to find that roading density was the only significant predictor. To minimise the impacts of harvesting on sediment delivery to streams, managers should focus on minimising the roading density and focus on breaking the connectivity between the sediment generated from roading and streams.

It did not appear that the site characteristics of terrain slope and stream length per ha made sites more susceptible to sediment breakthroughs, contradicting the consensus of the literature for most soils. Perhaps this reflects the stable nature of the Moutere gravels soil, with their low potential to produce runoff and moderate to good drainage characteristics.

Crew was not found to be a significant influencing factor, but there was inadequate replication in the sample of harvest settings. Detecting a difference between extraction methods was also unlikely due to the sample of only five ground-based sites, meaning there was a low power of test. The decision to exclude the site that was primarily shovel logged reduced this sample size further, which saw no significant influence of extraction method being detected in the revised model. This result was also potentially influenced by a low power of test.

For this kind of study, it was difficult to survey a collection of harvest settings that would have allowed adequate replication for all factors, due to the limited number of sites available at any one time. There was some confounding of extraction method with felling method, as two of 11 of the cable yarding sites were felled manually, while the others were mechanically felled. Even for the best model, 67% of the model variation is left unexplained. To achieve a satisfactory answer for the ultimate question of what the most influential factors for sediment delivery are, further research would be needed with a study design that allows for a greater power of test, less confounding, and with more factors included that are thought to influence sediment delivery of the Moutere gravels such as measures of ground cover and micro-topography.

It should be noted that the category of roads is not a perfect representation of the true roading density of modern harvest operations, due to the inclusion of legacy roads from previous rotations. These older roads are far less likely to be sources of concentrated sediment flows, and do not reflect current roading practices. Also, when some sites were observed, they were at various stages of the remediation process, meaning that some of the sediment breakthroughs will have been remedied since. Ideally, they should have been avoided or mitigated prior to remediation.

6.3 BARE SOIL CLASSIFICATION METHOD

The bare soil classification method could not reliably estimate bare soil percentage for harvest settings, so the null hypothesis stands. A visual inspection of the aerial photos (Figure 12) and the image classification for the reliability assessment suggested that it did not perform satisfactorily for several reasons. A harvested forest is a complex and heterogeneous environment to categorise, so the relatively coarse spatial resolution of 0.75m pixels may have led to many mixed pixels, which the maximum likelihood classifier would have struggled to categorise accurately. There was significant shading due to the time of day the photos were taken, resulting in large areas of bare soil on the skid sites that were misclassified as covered soil. Inaccurate geo-rectification of the images would have severely impacted the comparison, with the ground transects being misaligned with the image transect.

Using a UAV could achieve higher resolution images than for images from fixed wing aircraft, and with greater timing flexibility, reduce the chance of shading and unfavourable weather impacting image quality. Also, insufficient training samples for a large heterogeneous area was also a potential factor, as there may have been inadequate training pixels to sufficiently differentiate the signatures of the two classification classes. Experimenting with image processing and more sophisticated image classification techniques may have improved the reliability.

7 CONCLUSIONS

There was a greater observed sediment breakthrough rate for ground-based settings compared with cable logged sites. For both systems, most of the breakthroughs that delivered sediment to ephemeral streams originated from earthworks or harvesting related soil disturbance. Soil disturbance from extraction, although extensive in cable logged sites, resulted in few observed sediment breakthroughs to streams. The image classification method developed to estimate the bare soil percentage for a site was not sufficiently reliable enough to allow conclusions to be made from the data.

Roading density was the only statistically significant predictor of sediment breakthrough frequency found; site slope and stream length per ha were not found to significantly influence the rate of sediment breakthroughs.

Managers should focus on reducing roading density through careful road placement and focusing on breaking the connectivity between sediment generated from earthworks and streams. Further study that focuses on quantifying the rate that sediment that is delivered to ephemeral streams gets transported to perennial streams would put in perspective how significant the breakthroughs to ephemeral streams are to overall sediment yields from harvested catchments.

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9 APPENDICES

Appendix 1: Table showing stream channel length (m), harvest area (ha), stream length per ha (m/ha), breakthrough count, and breakthrough frequencies by setting. [1] *High lead,* [2] *swing yarder.*

Setting	Channel length (m)	Harvest area (ha)	Stream length per ha (m/ha)	Breakthroughs	Breakthroughs per stream km	Breakthroughs per ha
Ground-based						
N748-1	1225	8.28	147.95	7	0.01	0.85
N811-3	240	13.41	17.90	2	3.22	0.23
N713-15	264	4.68	56.41	6	6.26	0.37
N713-2	372	8.13	45.76	3	8.33	0.15
N839-1	567	10.80	52.50	7	12.35	0.65
Cable yarder						
T045-1 [1]	958	16.33	58.67	6	7.25	0.16
N838-1 [1]	414	18.85	21.96	3	5.14	0.09
N786-1 [1]	517	12.21	42.34	0	0.00	0.00
N786-2 [1]	332	7.47	44.44	1	0.00	0.00
N713-13 [2]	612	10.83	56.51	4	22.73	1.28
N713-10 [2]	389	21.21	18.34	2	6.54	0.37
N713-3 [2]	621	8.68	71.54	2	8.07	0.37
N807-3 [2]	25	2.88	8.68	2	6.62	0.26
N807-4 [2]	302	7.60	39.74	2	3.76	0.24
N807-5 [2]	266	4.19	63.48	1	8.35	0.45
N791-3 [2]	479	8.93	53.64	4	0.01	0.45

Appendix 2: Table showing setting coordinates, slope means and slope standard deviations.
[1] High lead, [2] swing yarder.

Setting	Latitude	Longitude	Mean Slope (degrees)	Slope Standard deviation (degrees)
Ground-based				
N748-1	41°29'30.563"S	172°55'37.96"E	17.7	6.28
N811-3	41°21'59.17"S	172°53'41.011"E	21.5	4.39
N713-15	41°24'57.032"S	172°52'47.664"E	27.3	7.1
N713-2	41°24'57.706"S	172°52'27.695"E	25.9	7.34
N839-1	41°38'24.548"S	172°52'59.499"E	16.6	6.72
Cable yarder				
T045-1 [1]	41°30'57.183"S	172°50'26.799"E	28.2	5.0
N838-1 [1]	41°30'10.004"S	172°50'3.026"E	28	4.9
N786-1 [1]	41°32'11.344"S	172°53'8.44"E	23.9	5.07
N786-2 [1]	41°32'8.696"S	172°53'23.576"E	24.1	6.2
N713-13 [2]	41°25'32.764"S	172°53'8.804"E	27.6	6.48
N713-10 [2]	41°25'16.315"S	172°52'51.425"E	28.4	5.48
N713-3 [2]	41°25'13.621"S	172°53'0.248"E	24.8	6.32
N807-3 [2]	41°27'25.685"S	172°57'42.57"E	21.8	5.44
N807-4 [2]	41°27'36.408"S	172°57'43.041"E	21.6	4.63
N807-5 [2]	41°27'43.69"S	172°57'39.438"E	19.9	5.47
N791-3 [2]	41°28'41.119"S	172°57'32.226"E	21.7	5.99

Appendix 3: Table showing setting soil characteristics and crew that completed the harvest operation. [1] High lead, [2] swing yarder.

Setting	Soil families		LUC	ESC	Crew
Ground-based					
N748-1	Spooner 65%	Norris 35%	7e11	Moderate	F
N811-3	60% Norris	40% Spooner	6e16	Low	E
N713-15	60% Norris	40% Spooner	7e11	Moderate	A
N713-2	60% Norris	40% Spooner	7e11	Moderate	A
N839-1	80% Donald	20% Kuranui	7e11	Moderate	F
Cable yarder					
T045-1 [1]	100% Donald	-	7e11	Moderate	B
N838-1 [1]	80% Kuranui	20% Donald	7e11	Moderate	B
N786-1 [1]	60% Norris	40% Spooner	7e11	Moderate	D
N786-2 [1]	60% Norris	40% Spooner	7e11	Moderate	D
N713-13 [2]	60% Norris	40% Spooner	7e11	Moderate	E
N713-10 [2]	60% Norris	40% Spooner	7e11	Moderate	E
N713-3 [2]	60% Norris	40% Spooner	7e11	Moderate	E
N807-3 [2]	no data	no data	6e16	Low	C
N807-4 [2]	no data	no data	6e16	Low	C
N807-5 [2]	no data	no data	6e16	Low	C
N791-3 [2]	no data	no data	6e16	Low	C

Appendix 4: Deep soil disturbance caused by a cable assisted felling machine slipping on a steep section of cutover. Although visually striking, this disturbances did not result in sediment breakthrough.

Appendix 5: A scalped ridge-top typical of cable logged sites.

Appendix 6: A track used by a tail hold machine that led down to a small ephemeral stream channel, showing signs of rilling. There was no slash cover or sediment control features to break connectivity.

Appendix 7: An ephemeral stream crossing at a ground-based site, where extensive soil disturbance is left bare allowing sediment to concentrate in the stream channel.

Appendix 8:Site where stems were shovelled downslope towards an ephemeral stream channel. Visible tracking scars from a felling machine leading to sediment breakthrough in two instances, and four breakthroughs from shovelled stems disturbing the old bench above the stream channel.

Appendix 9:A significant sediment flow path from a skid trail down to an ephemeral stream channel.

Appendix 10: A cut-out installed in a skid trail that channels runoff into an ephemeral stream channel.